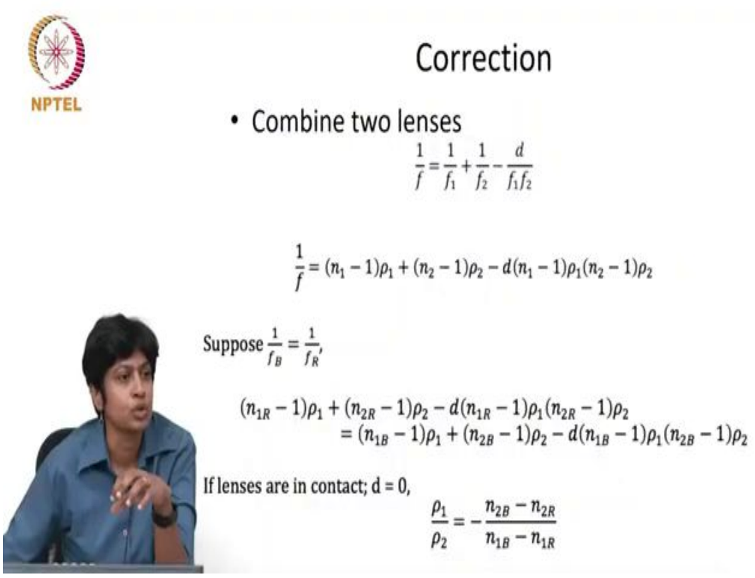
Optical Engineering
Prof. Shanti Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture – 21
Aberration correction

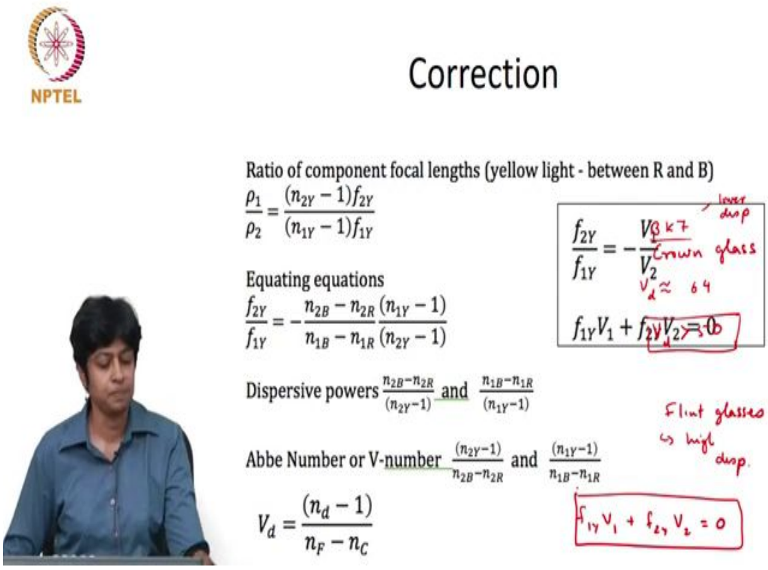
Good morning. So, today we will continue with Aberrations. We looked in yesterday's class; at chromatic aberration and we ended the class by looking at how we could correct it. So, just to refresh your memory, we said the idea is you want to correct chromatic aberration for at least two wavelengths.

(Refer Slide Time: 00:41)



So, you are not going to use a single lens because if you use a single lens, you have a single material. And since chromatic aberration is caused by the material we use, if we can somehow use two materials can we put two lenses each of a different material together and somehow come back to the chromatic aberration?

(Refer Slide Time: 01:05)



So, we started this derivation yesterday and in doing so, we also arrived at a parameter that is defined for every optical material called the V number and that basically tells you how dispersive that material is. Now up till now in all your classes lab classes you have been using B K 7 as a glass, now you should understand why you have been using B K 7 it turns out B K 7 is a crown glass. And we also calculated it as a V number and it was around 64 right; it was 64.5 or something.

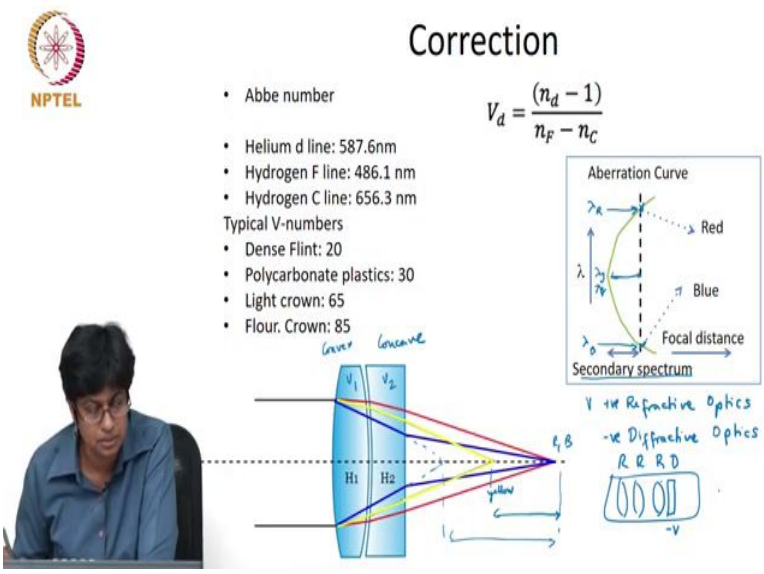
So, this is on the higher side and a higher V number means it is a lower dispersive glass ok. So, we use B K 7 because it has lower dispersion. And typically if you see there it's usually denoted as v_d. If $v_d > 50$, we call that a low dispersion glass. So, there are many different glasses, they depend on what chemicals that have been used to make the glass and the crown glasses tend to be lower dispersive glasses. They have higher V numbers, we will also have flint glasses and they will have slightly higher dispersion.

Now, it is important for us to use a combination of materials and our derivation showed us that if we have a two lenses and if the combination of the focal lengths and the V numbers of these materials gives us and I will just write it again $f_{1y}v_1 + f_{2y}v_2 = 0$. If this is satisfied for two lenses in contact, then you can eliminate the chromatic aberration for two wavelengths red and blue.

Now note that you have written this equation in terms of the focal length of each of those lenses. But it is the focal length at a middle wavelength; the wavelength that lies in the middle of the visible range. So, given that this is the focal length and let us say this is at yellow. So, this is a focal length for the lens 1 at yellow, this is a focal length for lens 2 at yellow. These are the V numbers of the materials used for each of these lenses. If this equation is satisfied, you would have corrected for chromatic aberration for red and blue ok.

Now the only way this equation can be satisfied if one of these terms somehow goes to 0 and we saw that the V number for optical materials was never going to go negative right. Because n of blue is always going to be higher than the refractive index of red light. Therefore the only way this equation can be satisfied is if one of the focal lengths is negative and therefore, that gives you this idea. You combine a convex and a concave lens and this is an idea we are going to use repeatedly even when you do correction of other aberrations ok.

(Refer Slide Time: 04:39)



So, in this figure below, you can see there is a combination of two lenses or convex and a concave. And here what is schematically depicted is you have light coming in that is a combination of all the wavelengths and because of the selecting the convex and concave such that it satisfies the equation that we just saw the red and blue are coming to focus at the same point whereas the yellow is still not focused at the same. So, this is an important point to get across.

When we say we are doing aberration correction, we are never or very rarely able to completely eliminate the aberration. Here it is not that the chromatic aberration has become 0. But if we have just had a convex lens, then we know that the light would have come to focus somewhere here right. If we had only a convex lens and then your spread of chromatic aberration would have been over this distance because you have combined two different lenses. So, you have taken a convex lens, you have taken a concave lens. Not only that they have different materials.

So, this has V number v_1 This is v_2. This combination has been corrected for red and blue. So, that red and blue get focused over here, but the yellow still gets focused over here. However; that means, your chromatic aberration now is spread over this distance much less than without the courage ok. So, thus this curve over here shows you. So, now, we go a step further. We normally in optics, we do not even label the axis here; we do not even draw the axis; you only draw the y axis and the y axis is, I have labelled it here. So, that is clear to you, but you might not see this label.

The y axis is wavelength and the x axis is focal distance ok. So, as you go from blue to red up the y axis, you can see here this is what each wavelength is focusing at and the fact that this curve actually bends and comes around like this. So, that both this point and this point have the same focal distance; that means, in other words this wavelength and this wavelength have the same focal distance. So, this is blue and this is red; that means, those two have been corrected, but you can see that the wavelengths over here and this would be like the yellow or the green wavelengths right.

These wavelengths still have that much difference, they are coming to focus at a point different from where the red and blue wavelengths are coming to focus and that this distance is called the secondary spectrum. It is like the unconnected or the leftover spectrum ok. So, this is one way of looking at the aberration curve for a system where some amount of aberration correction has been done.

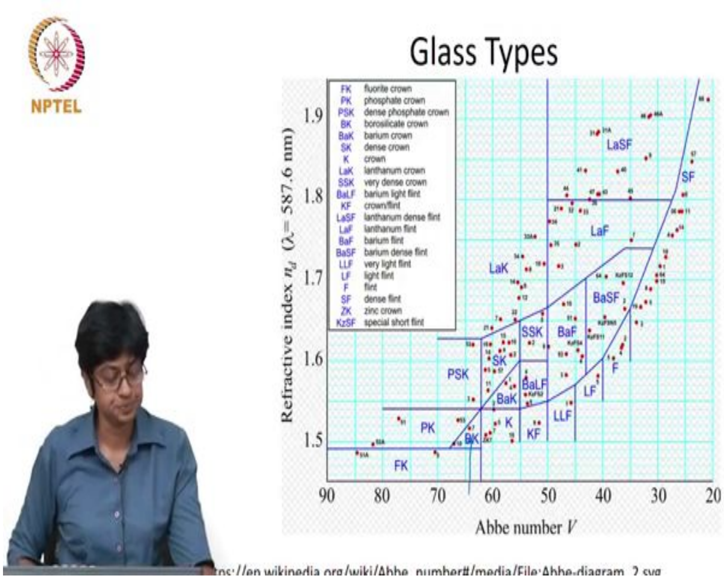
So, always remember that when we say we optimize to eliminate an aberration, yes you could move the stop to the natural stop position comma is 0 there. So, you actually eliminated comma, but not all aberrations can be completely eliminated. At best you eliminate them for under certain conditions and I will explain what I mean in some detail over the next few slides.

But you can get a sense of that in chromatic aberration when we do correction, we are actually saying we are correcting what you end up doing is actually correcting for some wavelengths; not all the wavelengths. We will not cover this in this class, but everything that we have been doing in this course has been related to refractive optics. So, we have been talking about taking dielectric optical dielectric materials, usually glass, you could also have plastics, but usually we've been thinking of glass and saying if you vary the shape you can make a lens which has a certain behaviour.

You can also have diffractive optics be. We will talk a little bit about diffraction later on in the course, but I can have a lens that is a diffractive lens. And the interesting thing to note there is I sent the V number when I took an optical material and it can never be negative. And so, the corrections that we had to do had to be done by introducing a lens with the opposite sign and that is why we took convex concave. Diffractive optics works on a completely different principle and will have a dispersion opposite in nature to that of refractive optics.

So, if we say the V number here is always positive, I can consider this to be negative. And so, I can take refractive elements and maybe onto this put a diffractive or add a diffractive element and because this has a negative dispersion, I can use this combination and correct for chromatic aberration ok. So, that is also possible.

(Refer Slide Time: 10:57)



We just wanted to show you this graph because I wanted you to get the idea of just how many different types of glasses they are. We just been using B K 7 because it is a standard crown glass that is used in a lot of optics. It has low dispersion, a higher V number and that is why it is relatively safe glass to pick.

But you can see that every red spot on this graph is a different glass type right and I mean this is only the glass types that are used in the visible range. And we have not even looked at what happens when we move into the ultraviolet, what happens when we move into the infrared or mid infrared or deep infrared and so on right.

These are only the glass types that we usually use in the visible range and you can see this such a huge variety of glass types. Why would you pick one glass type over another? Well one thing you now know is you would look at the abbe number and you would look at the dispersion and pick. And when you are combining convex and concave to reduce chromatic aberration, you would take a convex crown that is a convex with low dispersion plus a concave with a high dispersion.

So, a flint glass and combine those two to do that cancellation. So, that might be one reason why you might pick something which has higher dispersion. But you could go to all of these glass types and understand there are many different reasons why you would pick one over the other.

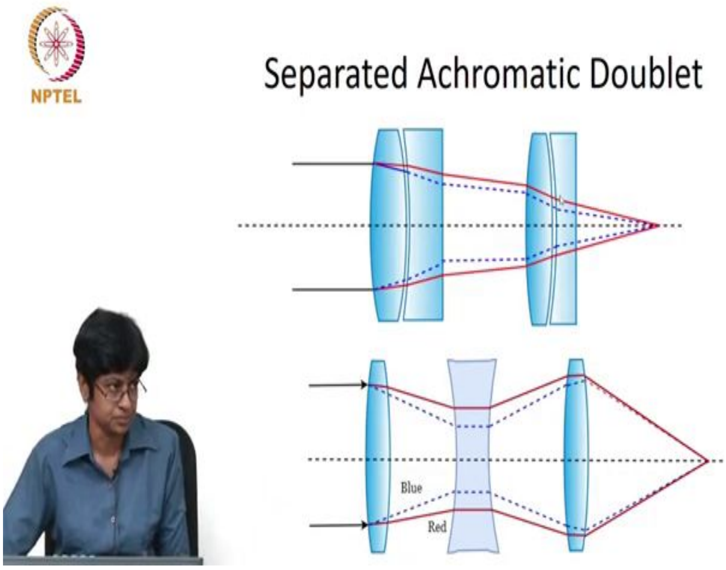
And we are not looking at those details in this course, but the glass is a very strong material, but even there you quantify the strength of the material. So, how easy is it to scratch? So, if you apply pressure with a sharp object and you apply that same pressure over many different glasses that kind of scratch, the depth of the scratch you get will be different and clearly you want for many applications you want the material to be scratch resistant.

So, you may choose one glass over another because of its physical properties. You may choose one glass over another because of its chemical properties, where it is being used, what temperature it is going to see. You do not want it to change shape or refractive index when it is in a higher temperature environment. So, you will look at its physical properties, its chemical properties, its optical properties. We have talked about refractive index. All of these glasses have different refractive indexes and you know now why the refractive index is. So, important, but what is not mentioned here is transmission of these glasses.

We just when we say glass, we tend to think it is a 100 percent transmissive and if you remember your Maxwell’s equations, you know that every time there is a surface there is a reflection. So, depending on the refractive index difference, some light is going to get reflected, but you want that to be as minimum as possible. There are things you can do to reduce the reflection. Let us see you do all of that; you still want the glass to be transmissive and not absorb big light. So, you have to look to see if these glasses absorb correctly.

So, all of those will be parameters you will take into account when you are actually choosing a glass type and some glasses will absorb in some regions of the visible more than in other regions and that might also be a reason why you pick one glass type over another. But this just shows you a snapshot of the wide variety of glass types that fit over there right and you can see our B K 7 is sitting over here. Abbe number greater than 60 right, ok..

(Refer Slide Time: 14:58)



So, as I said we do combinations now and you understand that the combinations would be negative and positive focal lengths, low dispersion plus high dispersion material. And every correction I do; now if I just take two lenses, you have already seen you can correct for blue and red light. But that may not be good enough for you, you may want to collect correct for more wavelengths. Then I need to put in more elements right. And you can see here you have different combinations and you might ask if two elements do the job, why go for more and more.

The question is two elements do not always do the job right. Why don't I always go for more elements then? Because of course the design complexity increases you have that many more variables to optimize and these are not problems where if I give each of you an optimization problem, the same optimization problem I am not going to get one solution and not because you make mistakes.

Assuming you all did everything correctly; if there are 18 of you in the room, I will get eighteen different solutions right away. If you are working in this huge space and you could end up anywhere in that space, it is a very difficult problem to solve right. So, you want to minimize the number of elements you are working with, you want to minimize the number of variables you are working with and every time you put in another element, then it is the material of that element, the focal length of that element, the shape of that element, the location of that element.

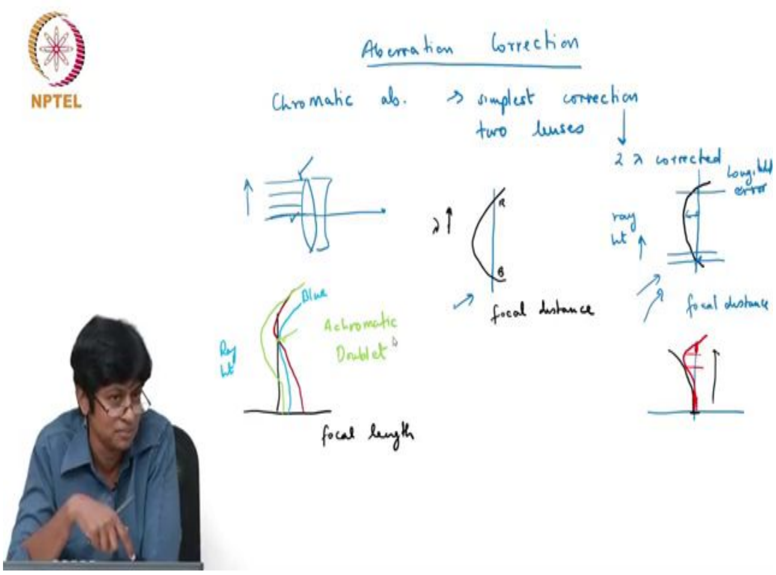
All of these parameters are just for one element added and now I do that I have to add all of these for every element added. So, you can imagine very quickly it can become an extremely complicated problem to solve. So, it is a trade off how accurate do you need your system to be, how much do you need the aberration to be corrected to how many elements are you willing to have in your system.

It also becomes bigger and more cumbersome to how much computational effort you are willing or able to put into it. So, all of that and then the glasses that you choose if I say I have to have very different glasses, they can start becoming expensive; so, the cost. So, all of this together will decide how many elements you need and then those are the ones you will use and optimize to get to a system with minimum aberration ok.

But you can see here just the first example has 2 elements, the top one has 4 and the lower one has 3 and you could choose any of these kinds of configurations. Each of them will give you some advantages while it may in some other sense give you a disadvantage because it may make the system more complicated or harder to calculate or optimise ok.

I just want to now kind of do a summary because we looked at. In fact, we come almost to the end of our geometric optics section of this entire course. We will move on to waves after this. So, if I look at what we been doing over the last few weeks, we been looking at aberrations, we went through what are the different mono chromatic aberrations, what causes them, where they are predominant, how do we quantify them and then we have also looked at the chromatic aberrations. And with the chromatic we did actually slightly detail look at how we correct them and I want to extend that idea now to correction in general ok.

(Refer Slide Time: 18:49)



So, you had this all idea already with the chromatic aberration that you correct the simplest correction was with two lenses and this gave you two wavelengths corrected. Now, one way of looking at that was the curve we had on the previous slide where we said it is corrected something like this.

So, this was λ and this was red light, this was blue light, this was focal distance. So, even though we said to it there is aberration correction, the correction was mainly for two wavelengths. I could also look at this in a different way. So, I can do focal distance, but this could then be ray height not wavelength and again over here, it could be that it is something like this.

So, you have to be very careful with the word aberration correction. Because up to now I said you can correct for two wavelengths, but it may be that you corrected for two wavelengths and those two wavelengths are best corrected for only one set of rays. Even those two wavelengths are not perfectly corrected for all the rays incident on the lens and that is what the second graph is telling you.

This is ray height. So, these are the rays on the axis. So, the rays on the axis are corrected to zero error or they come to this focal position. As you move up the lens so, you have a lens and you have raised incident different places on the lens. These rays we consider irrespective of lambda getting focused correctly. I am drawing a single lens. I am talking about a corrected system ok.

As you move up, these rays just because of the location on this corrected system are not being corrected. And then again the rays over here; so, you have correction here and you have correction here. So, you have to look at all these curves to understand what the actual correction is, it could be that you correct for different wavelengths, but you correct for those wavelengths for a set of rays at one annulus or certain zones of the lens. The rays incident on those zones are corrected, the other rays are not right.

So, this is nothing, but your longitudinal error kind of right. So, looking at this curve tells me two wavelengths are corrected, this curve tells me the paraxial rays in the marginal rays are corrected and they are still an error over ok.

So, this point I really want to stress: whenever you do correction, you are achieving correction, possibly for some wavelengths possibly for some rays. And when I say some rains rays I mean only some annular zones rays incident on those annular zones of the lens are corrected and not the others and that is why it is important to go and look at these transverse and longitudinal areas that are not transverse.

These are longitudinal aberration graphs of the wavelength aberration graphs. Because they tell you how well the correction is right. If you had no correction to this graph here, this graph here would look like this 0 error for the paraxial ray. As you go up with ray height the further and further rays experience more and more correction.

So, what is the correction for the addition of that second element? It is a curve changing the curvature of this. So, you do this and then it bends like this right. So, there is a region it is still unable to correct for, but it corrects over here and it retains the minimum particle. So, that is how you think of the correct.

And you will see these kinds of curves in all the kinds of aberration correction you do. So, I could also look at I mean this is also a typical graph that you might get. So, I have that blue nine. So, this is ray height ok, I am showing you a correction of aberration chromatic aberration might have something like this right and ok. So, you can see this point here red and blue are corrected; they have the same focal length.

So, for those heights raised those two wavelengths have the same focal length, but for any other set of rays falling on the lens, they have different focal lengths right. So, you need to look at all these aspects to actually judge the level of correction that has been achieved in a system.

And this is why you might use more than just two lenses; these graphs are typical of what you would get of what is called an achromatic doublet because you used two lenses for the courage. And you can see that while you achieve correction for two wavelengths for one annular zone of the lens. You have not achieved correction anywhere else or for any other wavelength and that may not at all be acceptable for your application.

In that case you know that a doublet is not going to work for you, you are going to have to add more lenses into the system with their spaces and use all of that to achieve much better correction than this.